Mass Based Constraints on Changing Flame Area

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Final Result

The Instantaneous Mass Burning Rate of a Premixed Turbulent May **Not** be Well Modeled by an Instantaneous Stretched Flame Area, but a Mass Constraint Leads to **Including the Local Rates of Change of Flame Area** in the Burning rate

Local Mass Flux of a Steady State Stretched Flame (kg/m^{2}s)

Local Time Scale for Thermo-Chemical Conversion of Reactants to Products by a Stretched Flame

$$\dot{m}_f = \int_{A_f} \dot{m}''_{s,f}(s)\left(1+\frac{\tau_M(s)}{\tau_A}H(\dot{A}_f)\right)dA_f$$

Instantaneous Mass Burning Rate of a Premixed Turbulent Flame (kg/s)

Stretch Rate

Time Scale for the Local Rate of Change of Flame Area

Heavyside Step Function

Flame Area Corresponding to Mass Flux Term

Note: All variables are a function of time

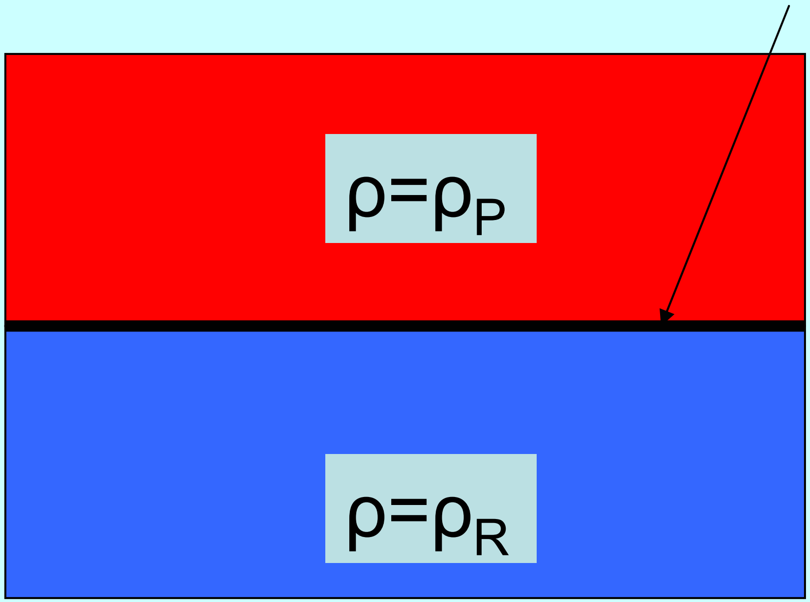
Final Result

- Interpretation
  - First term is classic stretched flame model
  - Second term, which results from mass constraint, reduces to zero for SSSF flames, but becomes increasing important with increasing turbulence (transient flames)
- Implications
  - Changes expectations so that increased burning at higher levels of turbulence can be attributed also to local rates of creation / elimination of flame area

Flames Have Mass

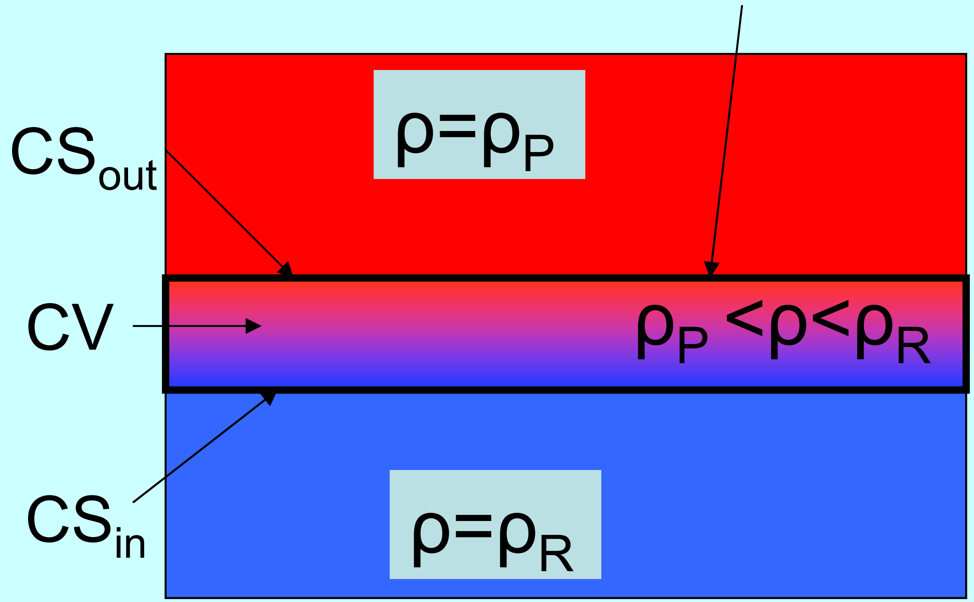
Consider SSSF Laminar Flame Experiencing Uniform Stretch Rate– Later Treat as Stretched Flamelets, which as an Ensemble models a Turbulent Flame

Interfacial Flame Model



No Control Volume, just Control Surface
No Flame Mass

Flame with Structure and Mass



Mass per unit area in Control Volume

$$m''_f(s) = \int_R^P sign(\rho_R - \rho(x)) \cdot sign(\rho(x) - \rho_P) \cdot \rho(x,s)dx$$

Time Scales

Rate of Mass Transfer Time Scale

$$\tau_M(s) = \frac{m''_{s,f}(s)}{\dot{m}''_{s,f}(s)}$$

Time it Would Take to Change
the Mass in Steady Flame

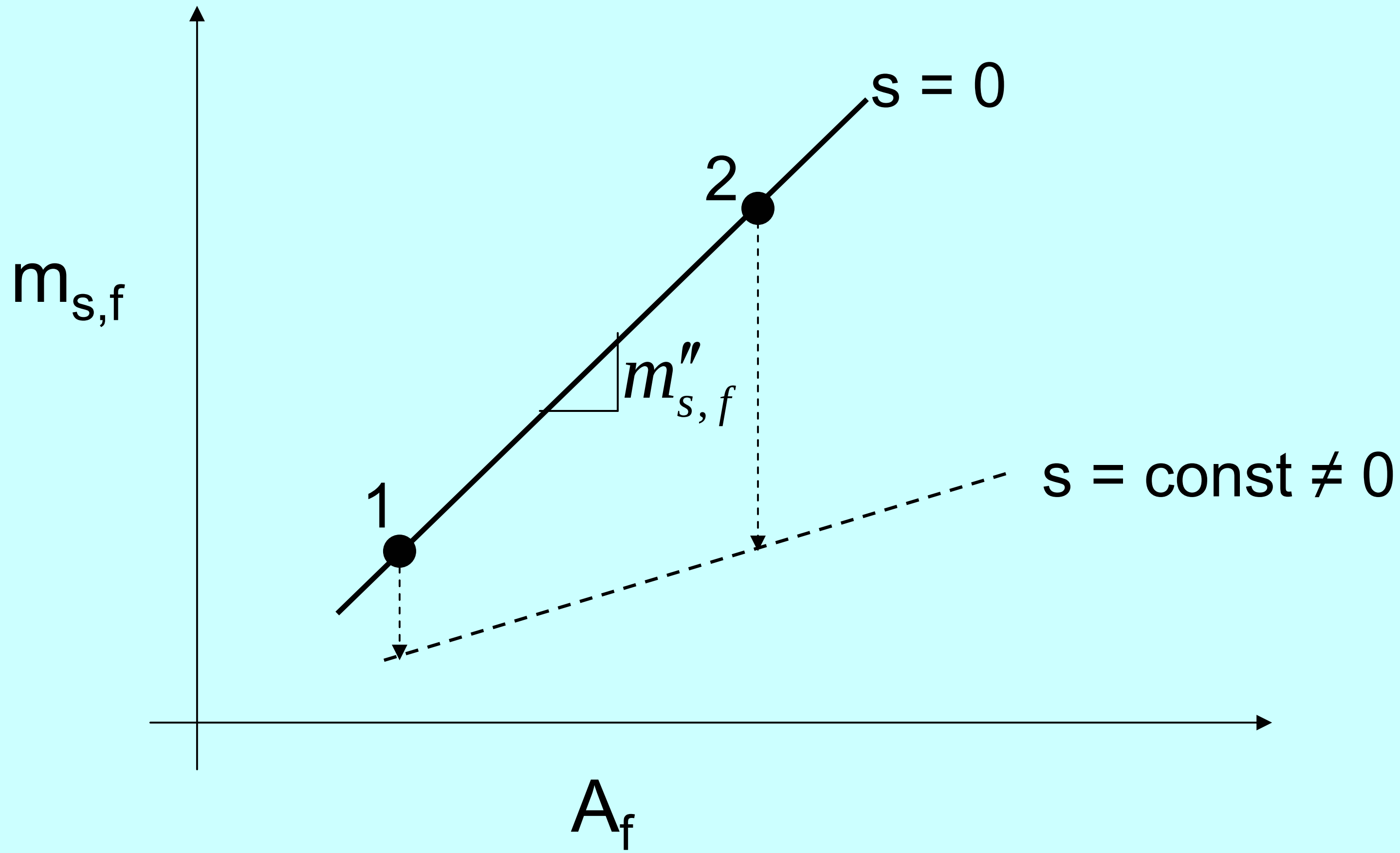
Rate of Area Change Time Scale

$$\frac{1}{\tau_A} = \left| \frac{1}{A_f} \frac{dA_f}{dt} \right| = \left| \frac{d \ln(A_f)}{dt} \right|$$

Time for Flame to Undergo
a Fractional Change in Area

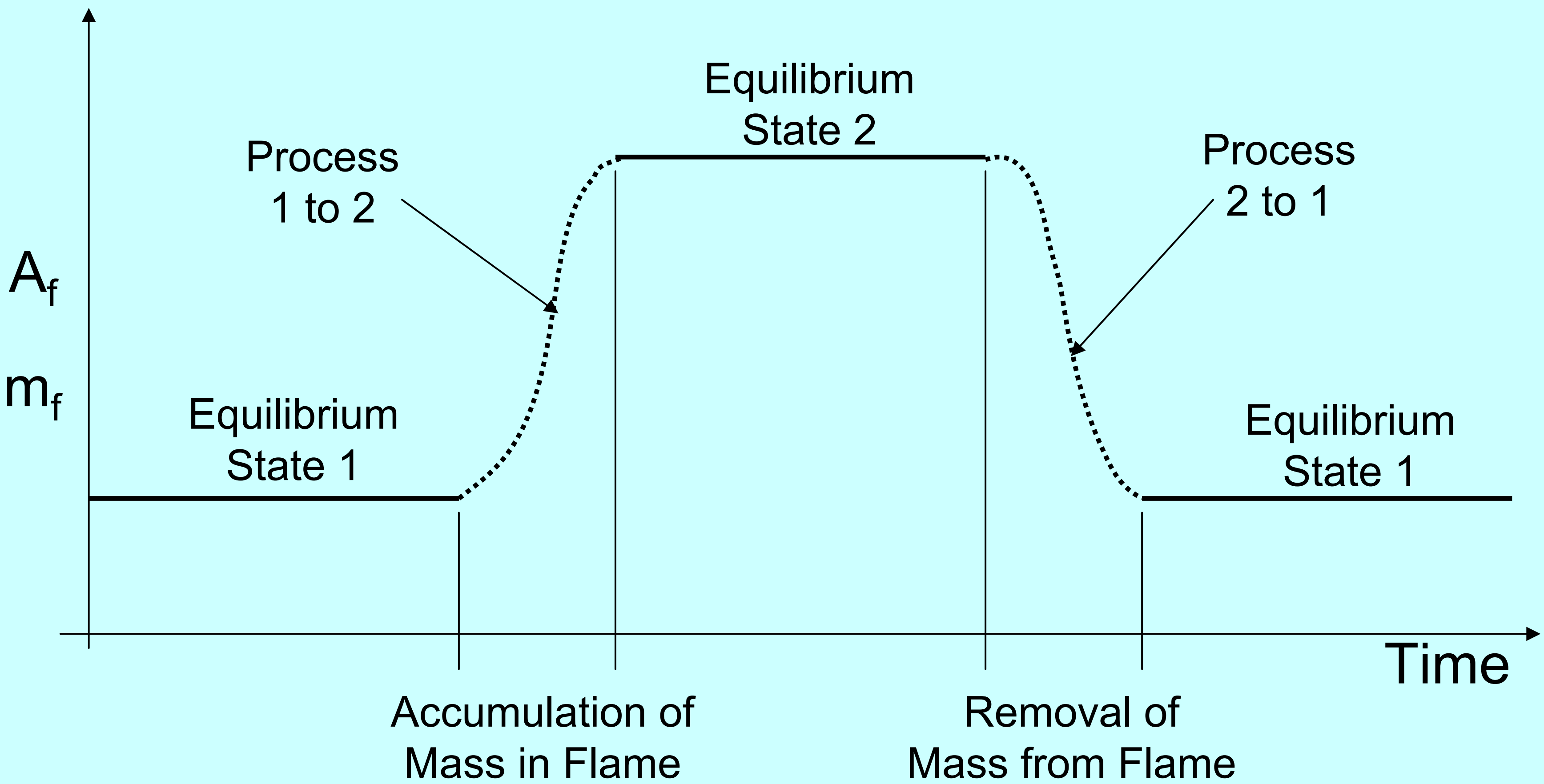
$\tau_M(s) / \tau_A$ Not Damkolher Number

Flame Area - Flame Mass

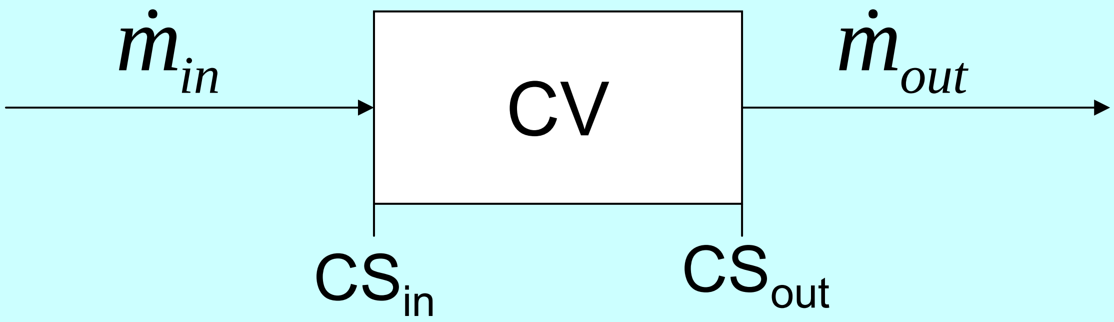


Cycle 1→2 then 2→1

First Create Area, then Eliminate Area



Constraints on Mass Flows

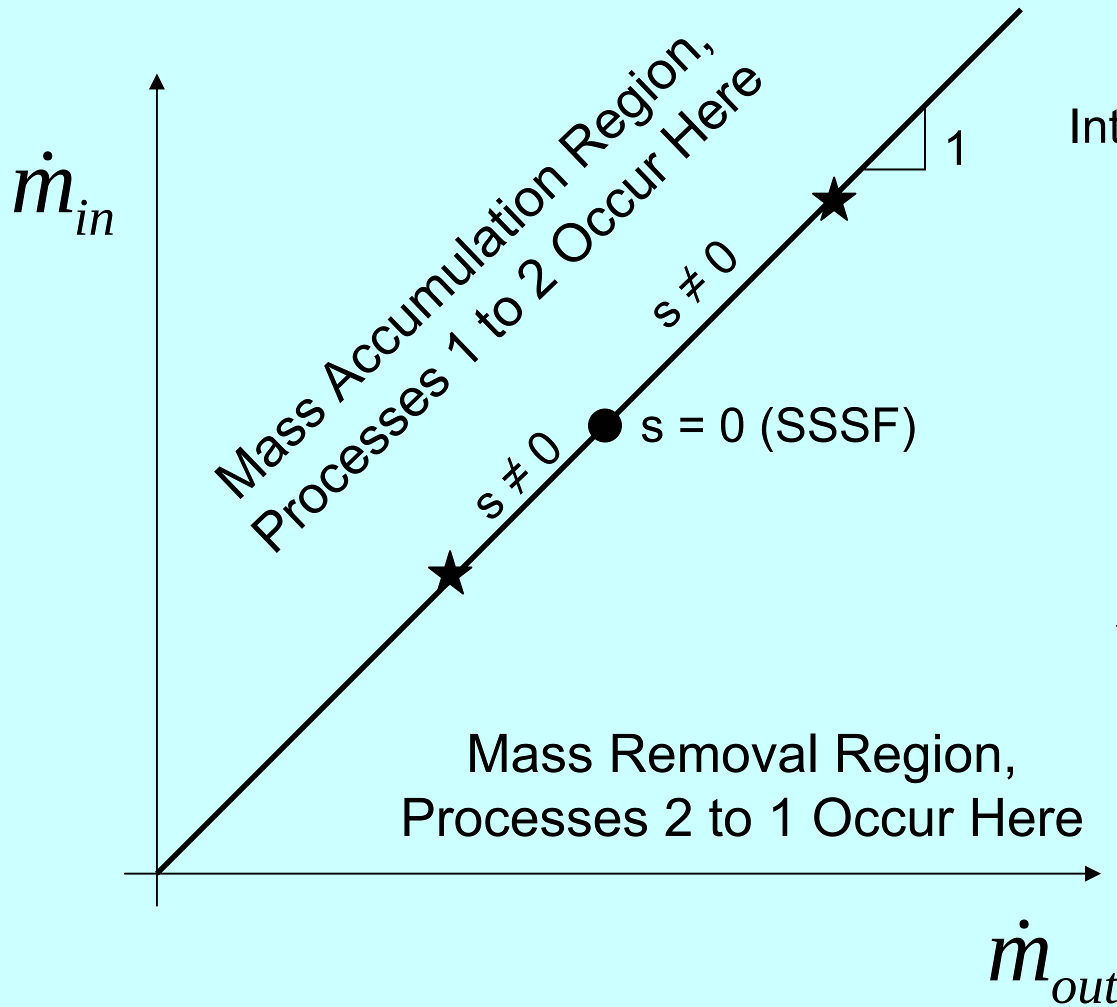


During Accumulation of Mass in CV $\dot{m}_{in} - \dot{m}_{out} > 0$

During Removal of Mass from CV $\dot{m}_{in} - \dot{m}_{out} < 0$

Constraints on Mass Flows

$A_f = A^*$, such that $A_{f1} < A^* < A_{f2}$



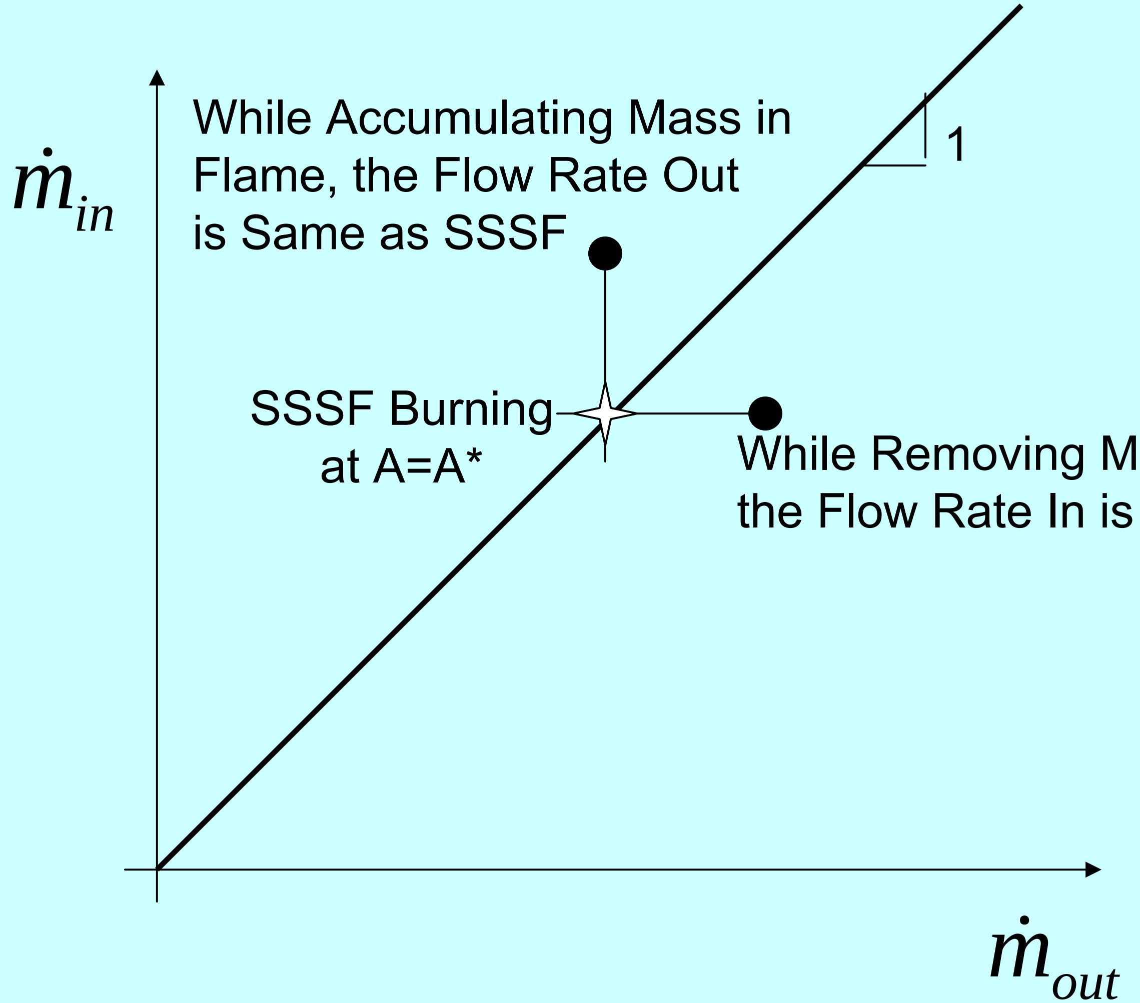
Line Represents Both SSSF Flames and Interfacial Flame Model

(i.e., $\dot{m}_{in} = \dot{m}_{out}$)

★ Extinction Limits

Models that Allow Changing Area to Participate Directly in Burning Rate

Illustrate with the extreme case, but any asymmetry affects burning rate



Follow mass flows at CS_{in} (or CS_{out})

Keeping Only First Order Terms

$$dm_f(s) = \dot{m}''_{s,f}(s) A_f\, dt + m''_{s,f}(s)\, dA_f$$

Based on Model Second Term Only Applies When Flame is Increasing in Size

$$\dot{m}_f(s) = \dot{m}''_{s,f}(s) A_f + m''_{s,f}(s) \frac{dA_f}{dt} H(\dot{A}) = \dot{m}''_{s,f}(s) A_f \left(1 + \frac{\tau_M}{\tau_A}\right) H(\dot{A})$$

Treat these Mass Burning Rates as Local Mass Fluxes of a Turbulent Flame
With Spatial Variations in Stretch Rate and Rates of Creation of Area

$$\dot{m}''_f(s) = \dot{m}''_{s,f}(s) \left(1 + \frac{\tau_M(s)}{\tau_A}\right) H(\dot{A})$$

Stationary Turbulent Flame

The Mean Burning Rate is the Time Averaged of the Mass Fluxes Integrated Over the Whole Turbulent Flame Surface

$$\overline{\dot{m}_f} = \overline{\int_{A_f} \dot{m}''_{s,f}(s)\left(1+\frac{\tau_M(s)}{\tau_A}\right)H(\dot{A})\,dA_f}$$

Conclusion: Due to a Mass Constraint on Changing Flame Area, the Burning Rate of a Premixed Turbulent Flame may be Increasingly Influenced by Increasing Rates of Creation (and Elimination) of Flame Area; and not just Instantaneous Flame Area and and the Influence of Stretch on the Thermo-Chemistry of that Area

Conclusion

Due to a mass constraint on changing flame area, the burning rate of a premixed turbulent flame may be increasingly influenced by increasing rates of creation (and elimination) of flame area; and not just instantaneous flame Area and the influence of stretch on the thermo-chemistry of that area.

Needs

Better understanding of transient flames in terms of mass fluxes into and out of flame

Better understand how the rates of creation of flame area relate to the turbulence in the flow (e.g., $\tau_A = f(\tau_T)$)